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The main objective of the program is to utilize nonlinear optical wave mixing for spsectrally parallel logic operations. In this program, we are invevstigating the parallel processing of information in the spectral domain. Specifically, we are investigating the optical implementation of spectrally parallel logic operations, including AND, XOR operations and logic inverter (also known as X-gates for set difference logic operations) using optical four-wave mixing in nonlinear media such as photorefractive crystals, Kerr media. The spectral logic inverter, for example, can convert the spsectrally encoded word of (1001) into a spectrally encoded word of (0110). In addition, we have also developed several new concepts in ooptical logic operations and optical computing. These include multiwavelength optical full adder with carry generaion, multiwavelength full adder with polarization encoding scheme, modified signed digit arithmetic for multi-input digital optical computing, multiwavelength multiple beam splotters, optical fuzzy set reasoning, etc.

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Spectral Logic Inversion using Optical Wave Mixing

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Final Report

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Table of Contents

1.0 Research Description
1.1 Scientific Problem
1.2 Scientific and Technical Approach
1.3 Publications

1.3.1 Papers Published
1.3.2 Conference Papers Presented

2.0 Progress
2.1 Progress Summary
2.2 Progress Details

3.0 Published Papers
3.1 PI's publication during 1993-1996
3.2 Reprints of Published Papers

1.0 Research Description

The main objective of the program is to investigate several unique concepts which utilize nonlinear optical wave mixing for spectrally parallel logic operations. In multiwavelength information processing (MIP), different wavelengths (or colors) are employed to encode, transmit and process information. The added dimension using wavelength has already been proposed for wavelength-division-multiplexed (WDM) fiber optical communication. In this program, we are investigating the parallel processing of information in the spectral domain. Specifically, we are investigating the optical implementation of spectrally parallel logic operations, including AND, XOR operations and logic inverter (also known as λ-gates for set difference logic operations) using optical four-wave mixing in nonlinear media such as photorefractive crystals, Kerr media. The spectral logic inverter, for example, can convert a spectrally encoded word of (1001) into a spectrally encoded word of (0110). The process requires the generation of new wavelengths at λ_2, λ_3 from the input wavelengths of λ_1, λ_4. In addition to our investigation in the area of spectral inverter logic operations, we have also developed several new concepts in the general area of optical logic operations and optical computing. These include, multiwavelength optical full adder with carry generation, multiwavelength full adder with polarization encoding scheme, modified signed digit arithmetic for multi-input digital optical computing, multiwavelength multiple beam splitters, optical fuzzy set reasoning, etc.

1.1 Scientific Problem

The investigation in this program on nonlinear optical wave mixing for optical computing has been focused on the development of nonlinear optical techniques for spectrally parallel processing. Specifically, we have proposed and demonstrated several unique concepts which utilize optical wave mixing in nonlinear media for logic operations in the spectral domain. During period of this program, we have successfully demonstrated a multiwavelength optical half adder by using four-wave mixing in photorefractive $LiNbO_3$ crystals and the implementation of a multiwavelength optical full-adder. In addition, we have also developed new concepts in the area of polarization-encoded optic logic operations in photorefractive media. In addition, we are also investigating the possibility of combining the wavelength and polarization encoding for spectrally parallel logic operations, as well as fuzzy optical logic operations using multiwavelength encoding. The spectrally parallel logic operations also play an important role in multi-value set logic operations for optical computing and WDM optical communication networks.

1.2 Scientific and Technical Approach

Consider the spectral logic inverter which converts a spectrally encoded word of (1001) into a spectrally encoded word of (0110) in the optical domain. The process requires the generation of new frequencies at ω_2, ω_3 from the input wavelengths of ω_1, ω_4. If all the frequencies are available locally, a spectrally parallel XOR operation can be employed to implement the spectral inverter. In other words, the logic operation (1111) XOR (1001) would yield (0110) in parallel. This is exactly the λ-gates for set difference logic operations. Such a multiwavelength XOR operation can be achieved by using a double Mach-Zehnder holographic interferometer in conjunction with a nonlinear media.

In the event when some of the frequencies are not available, nonlinear optical processes such as parametric three-wave mixing in $\chi^{(2)}$ media, or four-wave mixing in $\chi^{(3)}$ media (Kerr media) and photorefractive crystals can be employed to generate the new frequencies. The nonlinear optical processes would normally require local pump lasers at specified frequencies in order to generate new waves at the desired frequencies. The efficiency of the frequency conversion depends on the interaction length, nonlinear coefficients $\chi^{(2)}$ or $\chi^{(3)}$, and phase matching. In the report that follows, we first briefly describe the fundamental processes that are involved in the optical logic operations. We then describe the progress of the program.

Four-Wave Mixing (FWM or 4WM)

The incoming signal at carrier frequency ω_s is mixed with a local oscillator (pump wave) at frequency ω_p in a nonlinear medium ($\chi^{(3)}$-medium such as silica fibers, nonlinear (NL) optical fibers, quantum wells (QW's), etc.). As a result of optical four-wave mixing, a new wave at frequency ω_s' is generated with $\omega_s' = 2\omega_p - \omega_s$. Figure 1 shows the location of the new frequency ω_s' relative to the pump frequency ω_p.

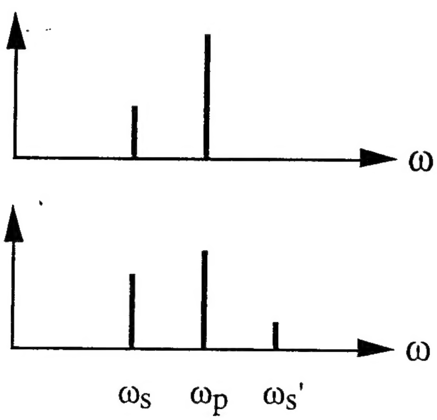

Figure 1(a). FWM-1

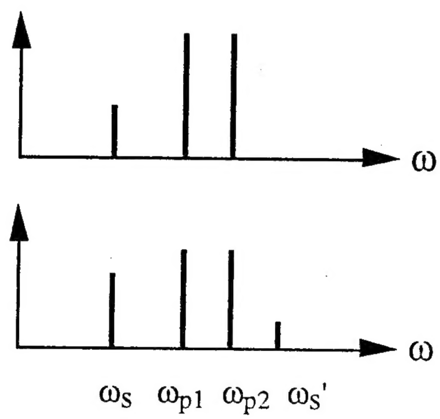

Figure 1(b). FWM-2

The energy efficiency of the mixing depends on the product of $\chi^{(3)}$ and the length of interaction L (i.e., $\chi^{(3)}L$ or n_2L), as well as the phase mismatch ΔkL. For silica fibers, the phase mismatch can be virtually zero provided the pump wave (ω_p) oscillates at the zero dispersion point where the group velocity dispersion (GVD) is zero. This can lead to a very efficient wave mixing for $\Delta\omega = \omega_p - \omega_s$ as large as 10^3 GHz. For other $\chi^{(3)}$-media such as semiconductor laser amplifiers (SLA), the phase mismatch is intrinsic due to the material dispersion. Thus the mixing efficiency is significant only for $\Delta kL << 1$ which translates into $\Delta\omega = \omega_p - \omega_s < 10$ GHz. The pump wave can also be replaced by two waves at different frequencies such that their sum frequency is $2\omega_p$ ($\omega_{p1} + \omega_{p2} = 2\omega_p$, See Figure 1(b)). New interaction configurations must developed in order to resolve the issue of phase mismatch in semiconductor laser amplifiers (SLA) or quantum wells (QW's).

Two-Wave Mixing (TWM or 2WM)

When the frequency difference between the pump wave and the signal wave becomes too large and ΔkL is also large, new frequencies can not be generated because of a phase mismatch. On the other hand, the phase mismatch is always zero for the mixing of these two original waves. Optical four-wave mixing in this regime is called two-wave mixing. In Kerr media with local response, there is no energy coupling between these two waves. Instead, there is a cross phase modulation between the waves. In other words, the phase of the pump wave is modulated with the signal carried by the signal beam, provided the signal beam is amplitude modulated. As a result of the mixing, the transmitted pump wave is phase modulated with the intensity information of the signal wave. Thus the signal originally carried by the signal wave is now impressed onto the pump wave which propagates at a totally new carrier frequency. In most Kerr media, the frequency translation can be as large as 10^4 GHz . The phase modulated wave can be converted into amplitude modulated wave by using a simple homodyne interferometric technique.

Three-Wave mixing (3WM)

In $\chi^{(2)}$-media (e.g., $LiNbO_3$, GaAs), the signal wave and the pump wave are mixed via an optical parametric process which is also known as three-wave mixing. As a result, the signal wave is amplified and an idler wave is generated at a frequency of $\omega_s' = \omega_p - \omega_s$. In quantum picture, the pump photon is split into two photons at ω_p and ω_s. The efficiency of the mixing depends on $\chi^{(2)}L$ as well as the phase mismatch ΔkL.

Phase matching ($\Delta kL=0$) can be achieved by using orthogonally polarized waves in properly oriented uniaxially birefringent crystals (e.g., $LiNbO_3$). Phase matching can also be achieved by using GeO-doped silica fibers with pre-recorded $\chi^{(2)}$-gratings. The frequency translation $\omega_s' - \omega_s$ using phase-matched three-wave mixing can be as large as 10^5 GHz. In this approach, the frequency of the pump wave is about twice of the signal wave in order to generate a new wave with a frequency shift of several GHz. For signals at semiconductor laser frequencies, the pump laser may not be easily available unless a simple and efficient second harmonic generation can be achieved.

We have been very successful in achieving the objective of the program by developing several novel concepts in spectrally parallel logic operations and validating these ideas experimentally using photorefractive materials. These novel concepts and experimental results are described briefly in the progress section 2.0. All these new findings and experimental results are published in professional journals and technical conferences. These publications are listed as follows:

1.3 Publications

The results of our research are documented in terms of technical journal papers and technical papers presented at professional conferences. Reprints of these papers are attached in section 3.2. The authors, titles and citations of these papers are listed below:

1.3.1 Papers Published

S. Zhou, S. Campbell, P. Yeh and H.K. Liu, "Modified-Signed-Digit Optical Computing using Fan-out Elements," Opt. Lett., 17 , 1697-1699 (1992).

C. Gu and P. Yeh, "Nonlinear Optical Matrix Multiplier," OE/LASE'93, Proc. SPIE Vol. 1853-28 (1993).

C. Gu, S. Campbell and P. Yeh, "Matrix-Matrix Multiplication by using Grating Degeneracy in Photorefractive Media," Opt. Lett., 18, 146-148 (1993).

P. Yeh, S. Campbell, and S. Zhou, "Optical implementation of a multiwavelength half-adder," Opt. Lett., 18, 903-905 (1993).

W. Wu, S. Campbell, S. Zhou, P. Yeh, "Polarization-encoded optic logic operations in photorefractive media," Opt. Lett., 18, 1742-1744 (1993).

S. Zhou, S. Campbell, W, Wu, P. Yeh and H.-K. Liu, "Polarization- and space-encoded parallel optical fuzzy logic processor," Opt. Lett., 18, 1831-1833 (1993).

C. Gu, S. Campbell, and P. Yeh, "Optical Matrix Multiplier: Grating Degeneracy Recycled," Optics & Photonics News, 4, 47 (1993).

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W. Wu, S. Campbell, S. Zhou and P. Yeh, "Optical implementation of carry generation for a multiwavelength full adder," Opt. Lett., 19, 646-648 (1994).

S. Zhou, W. Wu, S. Campbell, P. Yeh, "Optical Implementation of Fuzzy-Set Reasoning," Appl. Opt. 33, 5335-5347 (1994).

W. Wu, S. Campbell and P. Yeh, "Implementation of an Optical Multiwavelength Full Adder with a Polarization Encoding Scheme," Opt. Lett., 20, 79-81 (1995).

S. Zhou, P. Yeh and R. Nabiev, "Optimal design of dual-wavelength multiple beam splitters," Opt. Lett., 20, 109-111 (1995).

S. Zhou, S. Campbell, P. Yeh, H. K. Liu, "Two-Stage Modified Signed-Digit Optical Computing By Spatial Data Encoding And Polarization Multiplexing," Applied Optics, 34 793-802 (1995).

W. Wu, C. Yang, S. Campbell, and P. Yeh, "Photorefractive Optical Fuzzy-Logic Processor Based on Grating Degeneracy," Opt. Lett., 20, 922-924 (1995).

W. Wu and P. Yeh, " Energy Coupling By Partially Degenerate Four-Wave Mixing In Multichannel Lightwave Systems," IEEE Photonics Technology Letters, Vol. 7, 585-587 (1995).

Z. Wen, S. Campbell, W. Wu and P. Yeh, "Optoelectronic Fuzzy Associative Memory With Controllable Attraction Basin Sizes," Optics Letters, 20, 2125-2127 (1995).

1.3.2 Conference Papers Presented

C. Gu, J. Hong, and P. Yeh, "Volume Holographic Storage in Photorefractive Media," (Invited Paper), OCCC'92., Proc. SPIE Vol. 1812, 97-102 (1992).

C. Gu and P. Yeh, "Nonlinear Optical Matrix Multiplier," OE/LASE'93, Proc. SPIE Vol. 1853-28 (1993).

P. Yeh, S. Campbell and S. Zhou, "Multiwavelength optical half adder," in Optical Computing Technical Digest, 1993 (Optical Society of America, Washington, DC, 1993), Vol. 7, pp. 68-71.

C. Gu, S. Campbell and P. Yeh, "Optical matrix-multiplication using grating degeneracy in photorefractive media," in Optical Computing Technical Digest, 1993 (Optical Society of America, Washington, DC, 1993), Vol. 7, pp. 119-122.

S. Zhou, S. Campbell and P. Yeh, "Optical implementation of the modified signed-digit algorithm," in Optical Computing Technical Digest, 1993 (Optical Society of America, Washington, DC, 1993), Vol. 7, pp. 313-316.

W. Wu, S. Campbell, P. Yeh, "Implementation of a multiwavelength optical full-adder," in OSA Annual Meeting Technical Digest, 1993 (Optical Society of America, Washington, DC 1993), Vol. 16, p. 65.

W. Wu, S. Campbell, S. Zhou, and P. Yeh, "Polarization-based optical logic gates in photorefractive crystals, " in OSA Annual Meeting Technical Digest, 1993 (Optical Society of America, Washington, DC 1993), Vol. 16, p. 65.

P. Yeh, C. Gu, S. Zhou, and S. Campbell, "Recent Advances in Photorefractive Optical Computing," (Invited Paper), Paper T9, The 8th Conference of the Australian Optical Society, Sydney, February 3-5 (1993).

P. Yeh, "Nonlinear Optics and Computing," (Invited Paper), Second International Summer School and Topical Meeting on Applications of Nonlinear Optics, Prague August 16-20 (1993).

C. Gu and P. Yeh, "Applications of Photorefractive Media in Optical Computing," (Invited Paper), World Optical Conference'93, Shanghai, Aug. 30 - Sept. 3 (1993), paper WeL1, pp. 69-70.

P. Yeh, C. Gu, S. Zhou, and S. Campbell, "Photorefractive Nonlinear Optics for Optical Computing," (Invited Paper) Conference Proceedings of IEEE/LEOS Annual Meeting, 317-319 (San Jose, California, 1993).

P. Yeh, "Recent advances in photorefractive optical computing," (Invited Paper), III Escula Y Taller Internacionales En Fotonica, IV Encuentro Latinoamericano en

Optics, Laseres Y Sus Aplicaciones, Oaxtepec, Mexico, 21 de junio - 2 de julio (1993).

W. Wu, P. Yeh, S. Chi, "Frequency conversion by four-wave mixing in single-mode fibers," Proc. 1994 IEEE Conference on Nonlinear Optics, Materials, Fundamentals, and Applications (Waikoloa, Hawaii, July 25-29, 1994), pp. 332-334.

P. Yeh, "Photorefractive Phase Conjugators and Applications," (Invited Paper) The 55th Autumn Meeting of the Japan Society of Applied Physics, September 19-22, Nagoya, Japan (1994), pp. 1181.

W. Wu, C. Yang, S. Campbell, and P. Yeh, "Photorefractive Optical Fuzzy Logic Processor," in Optical Computing, Vol 10, 1995, OSA Technical Digest Series (Optical Society of America, Washington DC, 1995), pp. 186-188.

S. Zhou, S. Campbell, P. Yeh, H. K. Liu, "Two-Stage Modified Signed-Digit Optical Computing By Spatial Data Encoding And Polarization Multiplexing," Applied Optics, 34 793-802 (1995).

W. Wu and P. Yeh, "Power coupling by four-wave mixing in single mode fibers," Conference on Lasers and Electro-Optics, Vol. 15, 1995 OSA Technical Digest Series (Optical Society of America, Washington, DC., 1995). pp. 111.

W. Wu and P. Yeh, " Energy Coupling By Partially Degenerate Four-Wave Mixing In Multichannel Lightwave Systems," IEEE Photonics Technology Letters, Vol. 7, 585-587 (1995).

W. Wu, S. Campbell and P. Yeh, "Implementation of a multiwavelength photorefractive arithmetic logic unit," Technical Digest, Photorefractive Materials, Effects, and Devices, Aspen, Colorado, June 11-14 (Optical Society of America, Washington, DC 1995) pp. 532-535.

W. Wu, and P. Yeh, "Multiwavelength Optical Information Processing," International Topical Meeting on Optical Computing, Paper OWC47 (Sendai, Japan, 1996).

2.0 Progress

2.1 Progress Summary

During the period of the program, we have made significant progress in achieving the objective of the program. We have developed several novel concepts in the area of optical logic operation with spectral parallelism using photorefractive nonlinear optical effect. In addition, we have also developed several unique concepts in the general area of optical computing, including fuzzy logic operations, fuzzy associative memory, modified-signed-digit optical computing, etc. These concepts have also been demonstrated experimentally by using photorefractive crystals. The following are highlights of the progresses we have made under the support of this program. We are the first to propose and demonstrate the following:

- In Multiwavelength Optical Logic Operations
    - Optical Implementation of a Multiwavelength Half-Adder
    - Polarization-Encoded Optic Logic Operations in Photorefractive Media
    - Polarization- and Space-Encoded Parallel Optical Fuzzy Logic Processor
    - Optical Implementation of Carry Generation For a Multiwavelength Full Adder
    - Optical Multiwavelength Full Adder with a Polarization Encoding Scheme
    - Photorefractive Optical Fuzzy-Logic Processor Based on Grating Degeneracy
    - Optical Arithmetic Logic Unit using a Polarization Encoding Scheme

- In General Optical Computing
    - Modified-Signed-Digit Optical Computing using Fan-Out Elements
    - Optical Matrix-Matrix Multiplication by using Grating Degeneracy
    - Modified Signed Digit Arithmetic for Multi-Input Digital Optical Computing
    - Optical Implementation of Fuzzy-Set Reasoning
    - Dual-Wavelength Multiple Beam Splitters

These progresses will be briefly described in the next section. As all our works are documented in professional journals which are attached in the appendix. Details of the research results can be found from the reprints of these published papers in 3.2.

2.2 Progress Details

During the program period we have studied various schemes of digital optical computing by using nonlinear optical processes such as optical four-wave mixing in photorefractive media. In the area of multiwavelength optical logic operations, the progresses include, Optical implementation of a multiwavelength half-adder, Polarization-encoded optic logic operations in photorefractive media, Polarization- and space-encoded

parallel optical fuzzy logic processor, Optical implementation of carry generation for a multiwavelength full adder, Optical Multiwavelength Full Adder with a Polarization Encoding Scheme, Photorefractive optical fuzzy-logic processor based on grating degeneracy, optical arithmetic logic unit using a polarization encoding scheme. In addition to our research in multiwavelength information processing, we have also developed and demonstrated several novel concepts in the area of General Optical Computing. These include, Modified-Signed-Digit Optical Computing using Fan-out Elements, Optical Matrix-Matrix Multiplication by using Grating Degeneracy, Modified Signed Digit Arithmetic for Multi-Input Digital Optical Computing, Optical Implementation of Fuzzy-Set Reasoning. The following is a brief description of each of the progresses. Details can be found in Section 3.2 which contains reprints of the paper published.

We are the first research group to report the experimental demonstration of a multiwavelength half-adder which utilizes multiwavelength encoding and photo-induced index gratings in photorefractive crystals. Phase matched diffraction from multigratings is employed to achieve spectrally parallel arithmetic operations of CARRY, whereas multiwavelength holographic interference is employed to achieve spectrally parallel arithmetic operation of SUM. We also propose the use of phase-matched cross-polarization readout in uniaxial crystals to achieve collinear operation. The results indicate that a spectral parallelism of hundreds of bits is possible. In addition to the color encoding, we also propose and demonstrate optical logic operations using polarization encoding and wave mixing in photorefractive crystals. In our approach two orthogonal polarization states of light beams are employed to represent respective logic value of 1 and 0. All 16 two-input logic operations can be easily achieved by use of the recording and readout of photo-induced volume gratings in photorefractive crystals. We have also proposed and demonstrated an optical full adder. The details of these results can be found in section 3.2 of this report.

Another area we have been investigating has been the implementation of digital logic operations and devices utilizing four wave mixing in photorefractive media. In particular, we have been considering the implementation of logic gates and gate combinations for arithmetic logic units, multiwavelength carry generation for full adders, and a multiwavelength polarization encoded full adder. This work is an extension of our earlier efforts in multiwavelength half adders and polarization encoded logic gates. Arithmetic logic units are general gates that are constructed for mathematical operations. In our work on carry generation for full adders, we have utilized multiwavelength information processing (where each bit in a binary word is represented by a particular wavelength) and intensity encoding (where "on" is represented by the presence of light and "off" is represented by the absence of light). In this manner, we can exercise the full spectral bandwidth of our optical processing systems. With our carry generator, we were able to demonstrate an intensity-wavelength encoded optical full adder via four wave mixing in photorefractive media. To extend the process and functionality of our full adder, we then proposed and demonstrated a polarization encoded (where "on" is represented by the presence of one polarization state of light and "off" is represented by the presence of an orthogonal polarization state of light) multiwavelength full adder utilizing four wave mixing in photorefractive media. The polarization encoding scheme permits an easy, accurate implementation of the necessary XOR operation, as well as an efficient implementation of NOT gates. In this system, we are also able to implement a carry-save full adder to improve calculation rates. A detailed discussion of these devices is given in section 3.2 of this report.

During the same program period we have also been advancing efforts in fuzzy logic operations utilizing four wave mixing in photorefractive crystals. Fuzzy logic systems can be viewed as a morphology between discrete digital systems and continuous analog

systems. Fuzzy sets and processes are highly useful in problems containing a sense of vagueness, such as pattern recognition, chromosome classification, engineering design, and social interaction systems. In fuzzy logic, there exist a finite number of logical membership classes. This is in contrast to digital logic, where two classes (zero and one) exist, or analog systems where an infinite number of classes exist (over the interval [0,1]). For example, if a fuzzy logic system contains five classes, then its numerical values are set logically to (0.2, 0.4, 0.6, 0.8, 1). Therefore, any input or output value in the range of [0, 0.2] becomes a member of the fuzzy logic value of 0.2, any input or output value in the range of [0.2, 0.4] becomes a member of the fuzzy logic value of 0.4, and so on. Because numerical values are considered to be members of a given range, fuzzy logic operations are said to calculate or be membership functions. As the sixteen Boolean logic operations in digital logic can be composed of combinations of two or more Boolean logic operations, fuzzy logic operations can be composed of a fundamental set of primitive operations. These operations are the Conjunctive Normal form (which calculates the minimum of the maximum among a group of fuzzy variables), the Disjunctive Normal form (which calculates the maximum of the minimum among a group of fuzzy variables), and the Conditional Addition (which adds fuzzy variables, limiting the output sum to one). This group of fuzzy logic operations can be calculated utilizing four wave mixing and grating degeneracy in photorefractive crystals. We have performed these operations experimentally, and analyzed their prospective performance abilities, comparing them to conventional electronic processors. The details of these results can be found in section 3.2 of this report.

In addition to our works on optical computing based on nonlinear optical techniques, we have also carried out several schemes of optical computing based on optical fan-out elements. We have proposed and demonstrated a modified signed digit (MSD) arithmetic to achieve multi-input digital optical computing. Our approach utilizes hybrid addition-subtraction transformation (or weight operation) rules among multiple inputs. This results in operation speeds that exceed those of two-input MSD arithmetic for multiple input computing. Optical implementation of our proposed multi-input MSD arithmetic by utilizing spatial data encoding and an optical fan-out element is also demonstrated experimentally. We have developed new methods of optical fuzzy logic operations and optical fuzzy controller syntheses. These new methods have also been demonstrated experimentally by using optical fan-out elements to achieve multiple imaging and by using polarization-space/aperture encoding to represent fuzzy variables optically. All 16 fuzzy logic operations between two input variables have been achieved by use of simple polarization-space data-encoding and kernel operation scheme. In addition, we have also implemented a min-max composition-based fuzzy controller by use of an aperture-data-encoding and a double-multi-imaging approach. Our systems exhibit a high operation speed, a large information throughput, and a high signal-to-noise ratio. To accommodate multiple wavelengths in an MIP system, it is desirable to have optical fan-out element which can provide the multiple spots without spectral dispersion. We start by designing a dual-wavelength multiple beam splitters (DWMBS) to split a dual-wavelength beam into two beam arrays, one for each of the two wavelengths. These two beam arrays may have either the same dimension and structure or different dimensions and structures, depending on applications. We designed a 1x5 DWMBS that exhibits one-dimensional diffraction efficiency and uniformity of 83% and 98.4%, respectively, for a wavelength of 514.5 nm and of 85.1% and 98.0%, respectively, for a wavelength of 632.8 nm. The details of these results can be found in section 3.2 of this report.

3.2 Reprints of published papers .

1. "Modified-Signed-Digit Optical Computing using Fan-out Elements," Opt. Lett., 17 , 1697-1699 (1992).

2. "Matrix-Matrix Multiplication by using Grating Degeneracy in Photorefractive Media," Opt. Lett., 18, 146-148 (1993).

3. "Optical implementation of a multiwavelength half-adder," Opt. Lett., 18, 903-905 (1993).

4. "Polarization-encoded optic logic operations in photorefractive media," Opt. Lett., 18, 1742-1744 (1993).

5. "Polarization- and space-encoded parallel optical fuzzy logic processor," Opt. Lett., 18, 1831-1833 (1993).

6. "Modified Signed Digit Arithmetic for Multi-Input Digital Optical Computing," Appl. Opt., 33, 1507-1516 (1994).

7. "Optical implementation of carry generation for a multiwavelength full adder," Opt. Lett., 19, 646-648 (1994).

8. "Optical Implementation of Fuzzy-Set Reasoning," Appl. Opt. 33, 5335-5347 (1994).

9. "Implementation of an Optical Multiwavelength Full Adder with a Polarization Encoding Scheme," Opt. Lett., 20, 79-81 (1995).

10. "Optimal design of dual-wavelength multiple beam splitters," Opt. Lett., 20, 109-111 (1995).

11. "Two-Stage Modified Signed-Digit Optical Computing By Spatial Data Encoding And Polarization Multiplexing," Applied Optics, 34 793-802 (1995).

12. "Photorefractive Optical Fuzzy-Logic Processor Based on Grating Degeneracy," Opt. Lett., 20, 922-924 (1995).

13. " Energy Coupling By Partially Degenerate Four-Wave Mixing In Multichannel Lightwave Systems," IEEE Photonics Technology Letters, Vol. 7, 585-587 (1995).

14. "Optoelectronic Fuzzy Associative Memory With Controllable Attraction Basin Sizes," Optics Letters, 20, 2125-2127 (1995).